Noninvasive Estimation of Mechanical Properties of Arteries

James. F. Greenleaf, Cristina Pislaru, Xioming Zhang, Wilkins Aquino

Material properties of arteries such as stiffness vary with age, disease state, and with circulating vasoactive drugs and hormones. The responsiveness of arteries to these variables gives an estimation of the "health" of the artery.
We report a method of measuring the real time mechanical state of the artery by inducing a wave in the arterial wall with a force produced by ultrasound radiation pressure. We then measure the propagation characteristics of the resulting wave with a Doppler transceiver. By solving the inverse problem associated with an appropriate arterial wall model, we deduce the values of relevant material properties within the wall for the particular state the artery is in. In anesthetized pigs we have measured the arterial stiffness throughout the cardiac cycle, and during injections of vasoactive drugs such as nitroglycerine and epinephrine. We found that epinephrine can change the speed of propagation of an impulse wall wave by as much as 20%. The results indicate that the method can measure arterial wall mechanical properties consistent with assumptions required to form an appropriate model of the vessel. The method has higher temporal and spatial resolution than previous methods.

Introduction. Material property measurements in complex structures such as vessels and heart wall are key to estimation of state of these structures. We have done several experiments *in vivo* using the impulse method for characterizing vessel properties. The procedure is to use a focused ultrasound transducer to produce a high intensity pulse of ultrasound focused in the region of interest. In the case of vessel analysis, supported in a separate program, the point of focus would be the surface of the wall of the artery.

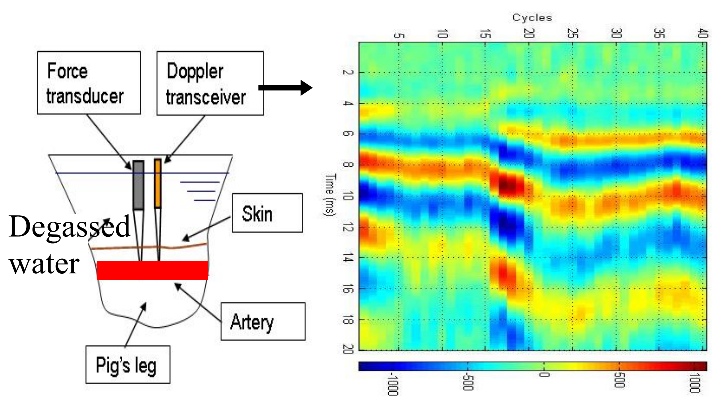

Figure 1 Left, schematic of experiment. Artery is moved with force transducer and motion is detected with Doppler transducer. Right, Doppler detected radial motion of pig femoral artery one centimeter from the point of an impulsive force produced with radiation pressure from a focused 3.0MHz transducer. Each vertical line is the measured motion at a fixed time point in diastole (red-away and blue toward the center of the artery). 40 heart beats are shown. At about heart beat 15, 0.5 μgram of nitroglycerine was injected into lumen causing relaxation associated with a decrease in wave speed.

Results. We show in Figure 1 that during relaxation of a femoral artery caused by nitroglycerine, the wave speed in the wall of the artery decreased, and during the relaxation, the viscous loss decreased for several heart beats as indicated by the increased magnitude of the wall motion. These data are not completely analyzed but are exciting evidence that shear wave propagation can provide a great deal of information about the material properties of the wall.

We also describe how FEM can be used for a sensitivity study of an impulse in a simple heart wall model, which indicates the possibility of finding an inverse solution for the elastic moduli in the heart wall from these types of data.

In order to determine whether we can calculate material properties of complex structures using a minimum of measurements we used Finite Element methods to calculate the response of structures to forces that could be produced using radiation force of ultrasound. The main objective of this work was to determine the sensitivity of the coupled acoustic-structural response of arterial vessels and the heart wall to changes in the material properties. This is a fundamental prerequisite for the inverse determination of elastic or viscoelastic properties of soft tissue using ultrasound radiation force. Finite element models of an anisotropic cylindrical vessel and an anisotropic plate immersed in a non-viscous fluid were built. Details of the finite element models, results, and conclusions are given below.

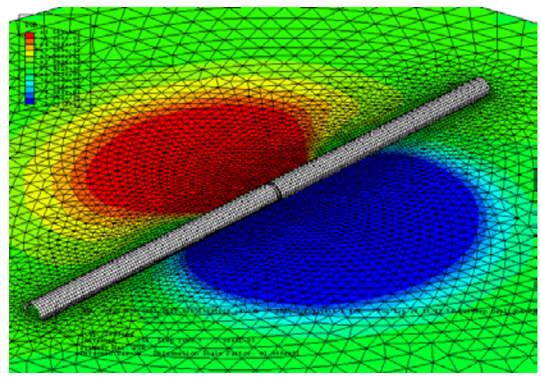

Figure 2 Acoustic field emanating from an impacted vessel.

A 3D finite element model of an anisotropic cylindrical vessel was built. The cylindrical vessel was represented with shell elements, which was filled with and surrounded by fluid elements. The cylindrical vessel was subjected to an impulse pressure. The velocity at a point on the surface of the vessel and the pressure in the fluid above the impact point were recorded over time. The commercial software ABAQUS Explicit was used in all the simulations. Figure 2 shows a cross sectional cut of a finite element model of a cylindrical vessel immersed in a fluid. The figure illustrates an acoustic pressure field emanating from an impacted vessel.

The material of the vessel was assumed to be anisotropic with principal axes oriented in the longitudinal and circumferential directions of the vessel. A parametric study was carried out by varying the elastic modulus in a given directions, while holding the other moduli constant. The elastic modulus (E) used for the sensitivity analysis varied between 0.5 MPa to 4 MPa, while Poisson's ratio was taken to be 0.49 in all cases to simulate near incompressibility.

Some of the results obtained from the sensitivity studies performed on the vessel are shown in Figures 3 and 4. It was found that the acoustic pressure in the fluid and the velocity at a point on the surface of the vessel are sensitive to changes in the circumferential elastic modulus. This indicates that it would be possible to inversely determine the circumferential elastic modulus from the acoustic field and/or surface velocities. Therefore, it is possible to quantify (non-invasively) material properties of arterial vessels using our vibroacoustic methods coupled with finite element analysis and optimization techniques that will be described in a later section.

The sensitivity of the acoustic pressure and surface velocity to changes in the longitudinal Young's modulus and the shear modulus was also investigated. It was found that the surface velocity is sensitive to both quantities, while the pore pressure is insensitive to changes in the longitudinal modulus. These results are not shown here for the sake of brevity.

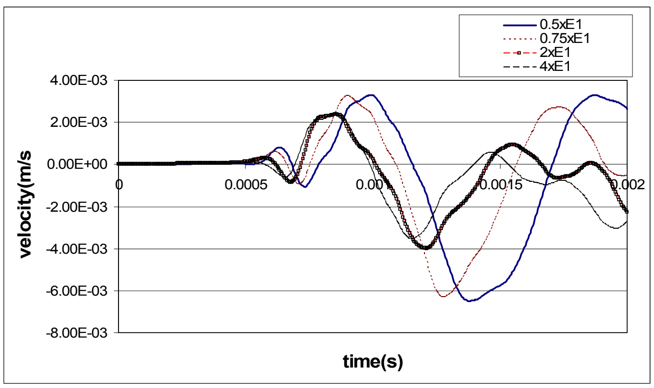

Figure 3. Normal velocity at a point 10 mm away from impact versus time, while varying circumferential Young's modulus (E1).

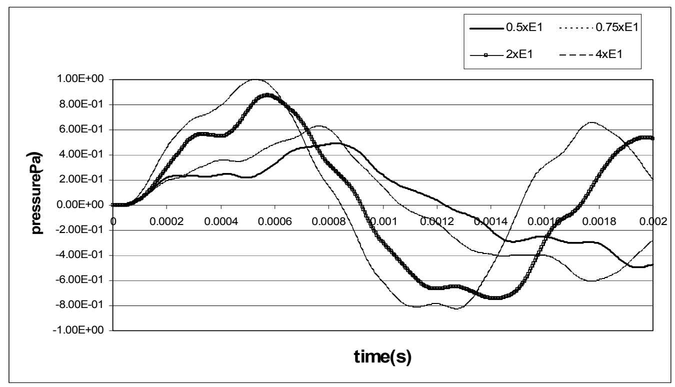

Figure 4. Fluid pressure at a point above the impact location versus time, while varying circumferential Young's modulus (E1).

Conclusion

The results of these experiments and others to be described in the talk are that using radiation force of ultrasound will elicit responses in complex structures that can be evaluated for the material properties of that structure.